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Preflight and Vicarious Calibration of Hyperspectral Imagers

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14. ABSTRACT
This report describes the work performed during the first year of the project to develop a comprehensive calibration/characterization plan describing methods to evaluate the alignment and focus of the optical elements, image quality based on the MTF of the system, stray light, spectral response, polarization sensitivity, detector-to-detector radiometric calibration in both a relative and absolute sense. In addition to the preflight characterization calibration plan, the work includes discussions of vicarious calibration approaches that act as a supplement to the onboard calibration systems to ensure that the sensor is behaving properly while in use.

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1. SUMMARY

The successful use of hyperspectral imagery depends upon the accuracy of the scene-detection/scene classification algorithms applied to the imagery. These algorithms, in turn, rely heavily upon the accuracy of the image data itself from a radiometric, spectral, and geometric standpoint. The work here is part of an effort to develop the capability for accurate absolute calibration of hyperspectral imagers to improve the accuracy of the subsequent products from algorithms operating on the data sets.

The work has been performed by the Remote Sensing Group (RSG) at the University of Arizona. Activities of the RSG include the well-known vicarious calibration work as well as laboratory-based studies to understand, develop, and improve preflight calibration techniques and equipment. Methods developed by the RSG as part of this effort lead to a comprehensive calibration approach for hyperspectral imagers using both laboratory and vicarious calibration approaches via the development of NIST-traceable laboratory procedures and equipment. These methods and instruments should provide hyperspectral imagery with accuracies rivaling that of laboratory-based multispectral instruments.

This report describes the work performed during the first year of the project to develop a comprehensive calibration/characterization plan describing methods to evaluate the alignment and focus of the optical elements, image quality based on the MTF of the system, stray light, spectral response, polarization sensitivity, and detector-to-detector radiometric calibration in both a relative and absolute sense. In addition to the preflight characterization calibration plan, the work includes discussions of vicarious calibration approaches that act as a supplement to the onboard calibration systems to ensure that the sensor is behaving properly while in use.

The key to successful vicarious and laboratory calibration is adherence to NIST traceability that ensures consistency between systems and within separate components of the same system. It is also important when vicarious methods are used because it helps to assess differences between the vicarious results and the preflight laboratory calibrations. The methods developed by the RSG for this project have the capacity to use primary, secondary, and tertiary standards of spectral irradiance (standard lamps) as well as primary standards of diffuse reflectance. The traceability ensures the best accuracy of the measurements, consistency of the results, and a transfer of laboratory measurements to the field.

The outcome of the work is a set of protocols and standard equipment that can be implemented in the preflight calibration to provide absolute radiometric and geometric calibration of hyperspectral imagers, both airborne and space-based. A similar protocol philosophy will be applied to the vicarious calibration that will allow calibration while in flight that is of similar accuracy to the laboratory results. The level of accuracy that is achieved will also be carefully evaluated and determined.

2. INTRODUCTION

The absolute calibration of a sensor begins in the laboratory during the final stages of the sensor's preparation for use. The typical approach from a radiometric standpoint is to have the sensor view an extended radiance source for which the output of the source is known. The use of an extended source is necessary to simulate the type of source that is measured by the sensor in flight. Radiance sources are either traceable to source- or detector-based standards (Yoon et al., 2002). In the case of a source-based standard, the given output of a source of spectral irradiance that is traceable to a national laboratory is transferred to the radiance source. Detector-based calibrations have the advantage of not relying upon an intermediate step but instead the output of the extended source is calibrated directly using the detector-based standard. *The accuracy of the actual sensor calibration in the laboratory depends on the individual calibration facility's skill at implementing a rigorous set of protocols and traceability to the standards chosen*.

If a set of well-defined protocols is followed during the preflight calibration process, it should be possible to compare the output of two sensors calibrated in different facilities or the output from multiple sensors calibrated in the same facility, but over many years. The output from these two sensors should agree to within the stated uncertainties when the sensors view a common source. This has been shown to be true in the case of a set of traveling transfer radiometers that have been compared through a series of round-robin exercises at several calibration facilities (Butler et al., 2002, Butler et al., 2003, Johnson et al., 1997). These round-robin exercises were made with carefully crafted, non-imaging radiometers and are an example of the best possible situation.

The work here includes five phases of activity to achieve an overall calibration approach for hyperspectral sensors under the purview of AFRL. The five phases are:

1. Expertise to develop a calibration facility
2. Development of equipment for an NIST-traceable calibration facility
3. Characterization of the facility
4. Characterization of the hyperspectral imager in the laboratory
5. Vicarious characterization of the hyperspectral imager

The next subsection gives an overview of the project by phase and the second subsection describes the overall project management. Section 3 of this report describes the technical aspects of the work done on the project followed by a discussion of measurement results in Section 4. Conclusions are given in Section 5.

2.1. Project Overview

The activities related to this aspect of the proposed work are analogous to the development of a calibration and verification plan for a system. The cal/val plan for most systems is typically developed well in advance of the actual sensor development, but this is not specifically required. This is especially true in cases where measurements of the sensor indicate the need for further characterization.

Note that the current work does not mention a specific sensor. One can argue that it is not possible to develop the cal/val plan for a sensor without knowing the specific sensor design. This is certainly true at the detailed level of sensor calibration. It is, however, possible to develop a measurement philosophy that is constant across sensors of all designs, as well as to define those measurements that are critically important to mission success. In essence, the proposed work will provide an hierarchy of measurements that ensure accuracy, NIST-traceability, and sensor understanding that is applicable to all hyperspectral systems.

As an example, consider the fact that the most accurate radiometric calibrations in the laboratory are done in a multispectral fashion. The outcome of this work will be to develop techniques that can be used to convert these multispectral measurements to a more suitable hyperspectral resolution. This will require methods to understand the spectral response of the multispectral sensors, the spectral output of the sources used in the laboratory work, and the scheme for converting to hyperspectral resolution. This has been done in the past using spectrometer data and modeled source output to interpolate between multispectral measurements, but this work has lacked the robustness to allow it to be applied in general cases and, more importantly, to understand the absolute accuracies of the results.

This cal/val plan will be developed through tests done in the RSG's calibration facility and by studying approaches of past systems such as Hyperion and AVIRIS. NIST-traceability will be through the currently accepted standards of spectral irradiance but the newer methods of reflectance and detector approaches will be investigated. The outcome will be a philosophical plan for calibration that describes the most important measurements for hyperspectral imager characterization, the impact of not making such measurements, and the hardware necessary for such measurements.

A primary goal of this activity is to develop a set of transfer radiometers that can be used to assess the spectral output of a variety of sources operating in the 400-2500 nm spectral range. Hardware in support of these instruments and recommended hardware for the most accurate sensor characterization will also be designed and implemented given sufficient funds. The important aspect of this work is that new methods for the transfer radiometers must be developed to improve their portability and their use in assessing the spectral output of a calibration source at hyperspectral resolution.

In addition to the algorithmic approaches to the transfer radiometers, there will be improvements to the systems that will further automate their use, make them more portable, and an assessment of the most appropriate wavebands to be used for hyperspectral assessment. The current sensors were developed specifically for two NASA-based multispectral imagers. Thus, the wavelengths were not optimally selected to allow an understanding of the source output at very short wavelengths and near the peak output of the source. Both of these wavelength regions are vital to understand the best spectral fit to the multispectral data.

The final step in developing the hyperspectral calibration capability is to calibrate the calibration facility. This ensures that the laboratory, hardware, and algorithms provide results that are within the accuracy goals of the program. Note that the previous two steps are done with the purpose of maintaining NIST-traceability. This, in theory, should provide a calibration facility of sufficient accuracy. It is possible for biases to be created in the laboratory during implementation, such as unanticipated stray light, interactions between the instrumentation and the local electrical grid, or simply errors in assembly of the laboratory. Measurements of the completed facility through a round-robin comparison approach will ensure that the calibration accuracy is as anticipated. This is accomplished using additional transfer radiometers to evaluate the newly-developed radiometers

The above work is not complete without actually calibrating the hyperspectral imager of interest. The RSG proposes to participate in the actual radiometric calibration of the imagers at the vendor's laboratory. This will include implementing the methods developed in the first part of the proposed work and can be combined with the facility characterization described above.

As mentioned above, vicarious approaches provide an independent assessment of the sensor's calibration once it is in operation. Vicarious approaches include a large range of possibilities that allow the sensor's radiometric, geometric, and spectral calibration to be determined.

The final step in the calibration process is to ensure that the sensor operates properly in space or while on the aircraft. This will be done via vicarious calibration. Past work has led to several general guidelines regarding the collection of vicarious calibration data in relation to trending versus calibration. The current level of 2.5% precision for radiometric calibration means that more than one sample is needed per month to ensure a statistically significant determination of a degradation of less than 10% per year. A precision of 1% would allow a 4% degradation to be seen with a 95% confidence interval. This is an important result since collecting more than one data set per month is not feasible.

Additional improvements in the vicarious results can be expected through improved characterization of the field instrumentation and development of new hardware. One proposed improvement is to expand the spectral sampling of the atmospheric measurements to include the SWIR spectral region. This will improve knowledge of atmospheric aerosols and their concentrations. Weatherproofing the current system design will allow the instrument to be left unattended for greater periods of time permitting the collection of vicarious data without the need for on-site personnel, thus allowing further data sets to be collected. These modifications, combined with collection protocols, should permit the calibration of the hyperspectral imager with uncertainties less than 2% in the mid-visible.

2.2. Project Management

This section provides information on the RSG team, and the Statement of Work defining RSG's role in the project. The anticipated deliverables for this project are:

1) The RSG will provide a completed set of protocols for preflight laboratory calibration that are applicable to hyperspectral imagers. The deliverable will be in the form of a calibration/validation plan document. The document will include methods for transferring multispectral data to a more suitable hyperspectral result. It also includes descriptions of methods for the laboratory determination of image quality and spectral accuracy.

2) The RSG will provide a completed set of protocols for vicarious calibration that are applicable to hyperspectral imagers. The deliverable will be in the form of a calibration/validation plan document. It will include methods for MTF, geometric, spectral, and radiometric calibration. The document will describe the required sampling rates and an accuracy assessment of results.

3) The RSG will provide a VNIR transfer radiometer for use in the laboratory calibration. The instrument will be based upon current versions but will include an automated collection scheme as well as spectral bands better suited for hyperspectral calibration.

4) The RSG will provide a SWIR transfer radiometer for use in the laboratory calibration. The instrument will be based upon current versions but will include an automated collection scheme as well as spectral bands better suited for hyperspectral calibration. In addition, a detector change to allow TE-cooling as opposed to liquid nitrogen-based thermal control will be implemented

5) An improved, automated solar radiometer will be supplied in support of vicarious calibration. This radiometer will include on-board GPS and barometric pressure as well as added spectral bands in the SWIR and further weatherproofing to allow extended operation.

6) The RSG will provide, in the form of a summary document, the results of any laboratory calibrations done as part of this proposed work.

The lead on this project is K. Thome who has been with the Optical Sciences Center since 1991 and is currently a Professor and Director of the RSG. Also working on this project are S. Biggar and E. Zalewski. Zalewski is a Research Professor in the RSG and developed the high accuracy absolute radiometric calibration technique known as Predicted Quantum Efficiency or Self-Calibration of solid state photodiodes. Biggar is a Research Professor in the RSG and his work on the project is related primarily to optical system design, evaluation, characterization, and calibration.

3. TECHNICAL APPROACH

3.1. Transfer Radiometers

The development of NIST-traceable, highly stable radiometers is an essential element in laboratory characterization of imaging sensors to determine the radiometric calibration. These radiometers, also termed transfer radiometers (TR), allow the evaluation of the accuracy of laboratory sources.

Transfer radiometers can provide independent calibrations of prelaunch sources and a cross calibration between various sensor sources. A transfer radiometer can also contribute valuable information with respect to vicarious calibration efforts by providing cross comparisons of the various sources and radiometers used by the numerous calibration teams. The ability to cross calibrate multiple sensors over a duration of 15 years, and to validate their corresponding calibration processes, clearly demonstrates the value of transfer radiometers. The overall benefit is that imaging data can be set to a defined radiance scale by the elimination of, or the significant reduction of, calibration errors.

Two radiometers are planned under this activity; one for the visible and near infrared (VNIR) and the other for the shortwave infrared (SWIR). The development of the SWIR TR is to take place during 2007.

3.2. Multispectral to Hyperspectral Conversion

The measurements by the TRs are at multispectral intervals. The requirements are to develop a hyperspectral calibration and, thus, a method for predicting the hyperspectral output of a laboratory source is needed. Typical methods for doing so are to model the spectral output of the source or to measure the spectral output with a spectrometer system. The difficulty with the spectrometer data is that the results are typically of lower accuracy than the multispectral data set. Thus, it is not feasible to use the spectrometer alone, and the combination of the high-accuracy TR data and the high-spectral-resolution spectrometer data gives the need for spectral sampling at a high level of accuracy.

3.3. Calibration/Validation Plans

One method to ensure the proper implementation of the TR results and evaluation of the hyperspectral calibration is the development of a comprehensive calibration/validation plan. The plan should be applicable to hyperspectral sensors as well as include discussions of calibration efforts beyond radiometric characterization. The key to the cal/val plan is to ensure NIST-traceability, primarily through the currently accepted standards of spectral irradiance, but able to use newer methods of reflectance and detector approaches. The outcome is a philosophical plan for calibration describing the most important measurements for the characterization of a hyperspectral imager, the impact of not making such measurements, and the hardware necessary for such measurements.

The calibration/validation plan ties together the two topics above as well as other more general characterization approaches. Figure 1 shows an example of the traceability evaluation. The importance of this figure is that it illustrates where the measurements by a transfer radiometer (TR) fit within the calibration of a hyperspectral system. The figure also illustrates the use of additional radiometers, including the RSG TRs and field spectrometers.

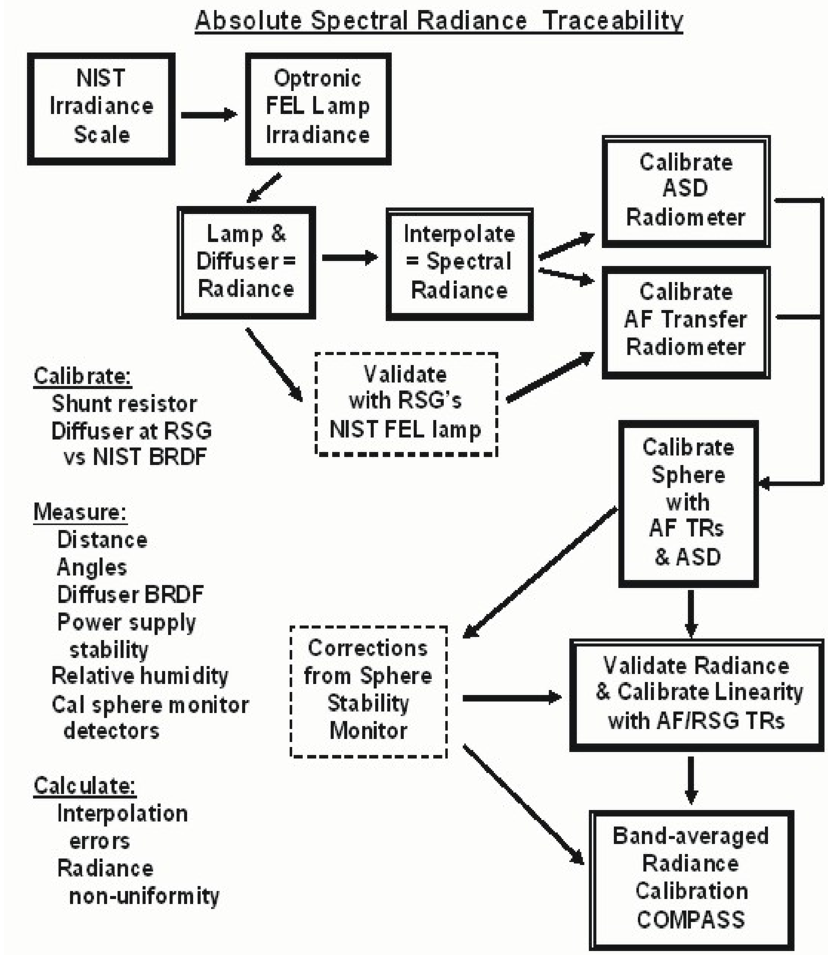

Figure 1. **Preliminary traceability flow for hyperspectral, radiometric calibration in the laboratorv.**

4. RESULTS AND DISCUSSION

4.1. VNIR TR Development

The optical design of the VNIR TR in this work is effectively a duplicate of the existing VNIR TR in the RSG laboratory. Details of the mounting of the electronics and the power supplies and data collection equipment are different but functionally the same. The system is operated via a Labview interface to the radiometer using a Windows PC. Other improvements over the past version of the VNIR TR include the original data logger model being replaced by an Agilent 34970A due to its higher accuracy and built-in IEEE-488 interface. An automated Sutter filter wheel is implemented rather than the manual filter wheel used in the existing VNIR TRs. This allows for automation of the data collection and reduces the possibility of errors associated with manual selection of filters. The Sutter filter wheel and power supplies are electrically-quiet, linear-pass type supplies designed by Sutter to minimize noise radiated to sensitive electronics like the detector amplifier. A similar wheel has been used in the RSG's VNIR BRDF measurement facility and has worked well when mounted near a detector and amplifier with high gain similar to that required for the VNIR TR.

The detector mount was modified slightly to accommodate improved amplifiers and a different heater design. The radiometer makes use of large-area, windowless Hamamatsu detectors and precision feedback resistors. Military-specification electrical connectors are used to reduce noise. Power supplies for the amplifiers are not as low-noise as the original supplies which are no longer available, but as shown below, this is not an issue since uncertainty analysis shows this to be a very small part of the expected error. A key improvement is the development of mechanical drawings using Solidworks which allowed evaluation of parts compatibility prior to assembly and will simplify development of further TRs especially the SWIR version.

Selection of spectral filters was based on the original VNIR TR in combination with the expected use of the radiometer in predicting hyperspectral source output. The results of the multispectral to hyperspectral source fitting approaches described in the next section were not mature enough at this stage to use in VNIR selection, but the modeling work shown in the next section shows that the filters chosen are more than adequate to model the source output.

The bands chosen for the radiometer are centered at 413, 443, 489, 552, 672, 746, 801, 874, and 1048 nm. Spectral bands were chosen to span the VNIR while avoiding spectral absorption features. The spectral bands have been characterized on the RSG's double pass monochromator and sample results are shown in Figures 2 and 3 for the 413-nm filter. All filters were characterized both in-band (Figure 2) and for out-of-band leaks (Figure 3).

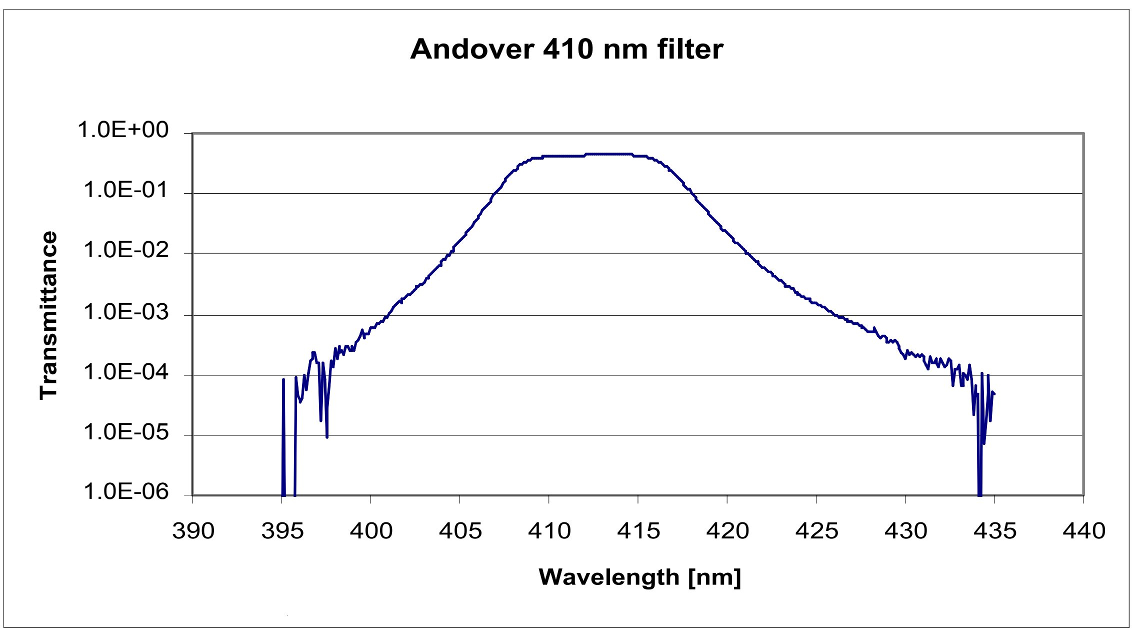

Figure 2. In-band spectral characterization of Band 1 of the VNIR TR.

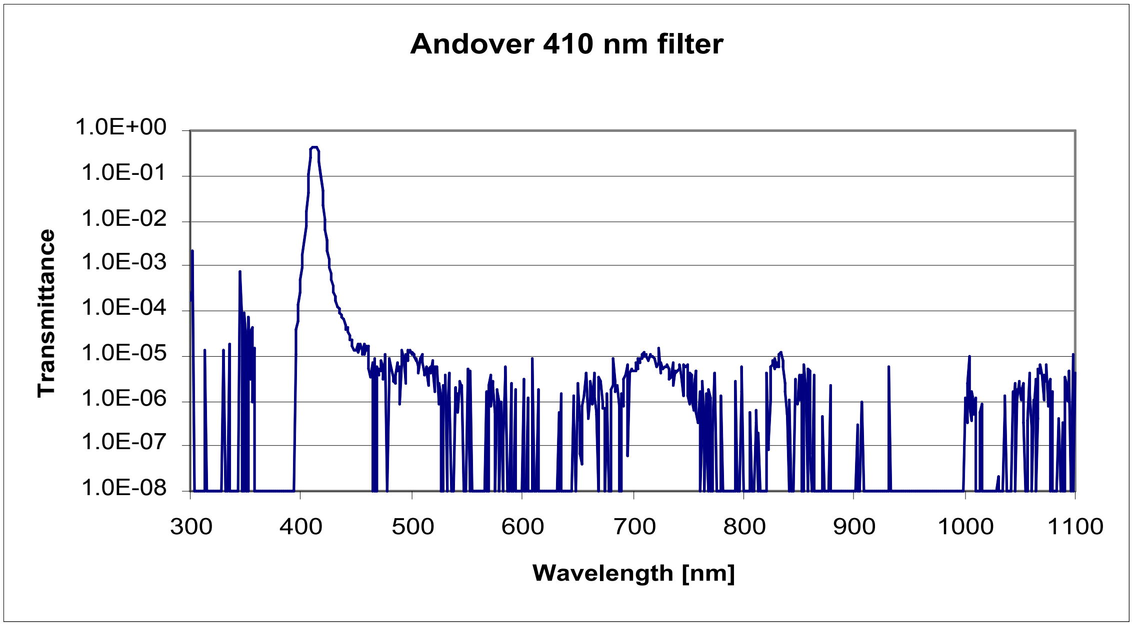

Figure 3. Out-of-band spectral characterization of band 1 of VNIR TR.

The radiometer saw its first light in September 2006. Figure 4 shows the radiometer in front of RSG's 40-inch SIS. Evaluation and characterization of the radiometer included field-of-view (FOV) measurements, noise evaluation, gain ratios, linearity, stability, and repeatability.

Figure 4. VNIR transfer radiometer at first light in front of 40-inch SIS.

FOV testing involved the RSG's off-axis collimator coupled with the 6" diameter Spectralon SIS with 125 Watt lamp and 2" diameter port. The SIS lamp was operated at constant current. The source was adjusted to slightly underfill the collimator primarily to minimize stray light and the room was baffled so the radiometer viewed only the collimator or a black baffle (which was not illuminated). The radiometer was rotated about the front aperture centered in the collimated beam and data were collected without the filters to enable large dynamic range (filters will slightly broaden response and raise wings due to scattering). The designed FOV based on a 4-mm diameter aperture with 100-mm separation is ± 2.29 degrees. The results from the measurements of the FOV show that the interpolated normalized signal is down to less than 0.03 at ± 2.29 degrees. The FOV results are shown in Figure 5.

Noise measurements began by allowing the radiometer to stabilize for 1 hour of operation. The offset was measured for various gain settings with 100 samples at a time to allow sufficient statistics for evaluation of the noise. One hundred sample measurements were then made of the RSG's large SIS operating at multiple lamps. The noise on the offset for original VNIR TR is approximately 6 microvolts. The current TR is showing values smaller than this when measured with the HP3458A without the 34970A scanning. Noise on a stable source typically allows an "SNR" that is based on an offset-corrected signal divided by the sum of standard deviations of signal and offset to have values greater than 10,000 for the original TR in most bands. The SNR when viewing a single FEL-type lamp illuminating a Spectralon panel at 50 cm is typically larger than 2000 for the original VNIR. Values for the current TR are better than these values. The SNR is lowest in blue as predicted based on the silicon response and improves as wavelength increases.

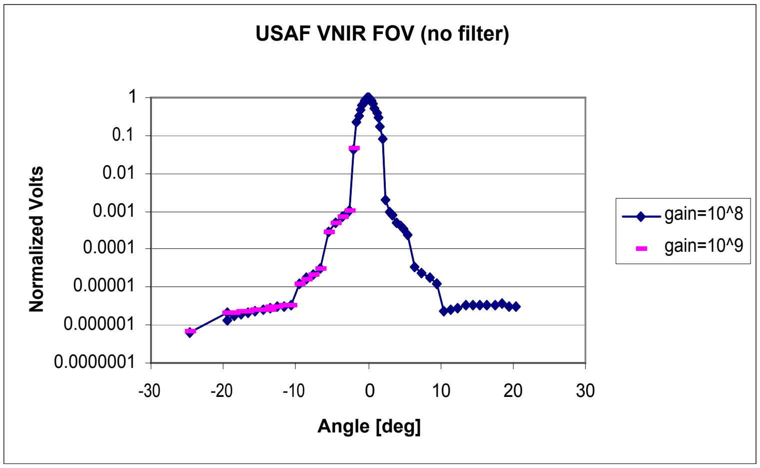

Figure 5. **FOV characterization results for VNIR TR.**

The goal of the gain setting was to achieve factors of 10 between gain settings with an uncertainty of 0.05%. Gain evaluation was accomplished by viewing a source that leads to a large signal value at the highest gain then adjusting the gain. Measurements of the gain settings indicate uncertainties of 0.03 to 0.08%.

Silicon trap radiometers with a good amplifier should be linear over a very large range of input radiance levels (many orders of magnitude) as long as diodes and amplifier are not saturated. Testing of this is difficult due to stray light, repeatability of the source, and ancillary measurements such as distance. Linearity tests were made in both an absolute and relative sense. Absolute linearity relied on measurements by the calibrated radiometer viewing an FEL lamp at multiple distances and relying on the distance-squared relationship. Relative linearity is determined by operating an SIS at multiple levels, monitoring the SIS with a "known good" radiometer. The SIS measurements are converted to the required wavelengths and compared to the measurements by the test radiometer. Early evaluation shows the system to be extremely linear, as expected.

Stability and repeatability evaluation relied on repeated offset measurements after warm up from cold start. Repeated radiometric calibrations were also made using the same FEL source. The third method was to make repeated measurements of a source that is characterized by another stable radiometer. Bands 3-9 show repeatability at the 0.1% level with bands 1 and 2 showing repeatability of 0.4% and 0.2% respectively. These values are slightly larger than those of the original radiometer but are more than sufficient to provide hyperspectral characterization of the sources used for the hyperspectral imagers.

Radiometric calibration was based on multiple methods including direct FEL view, FEL illumination of a diffuser panel, the RSG SIS, and a solar radiation based calibration (SRBC). The FEL calibration, or irradiance calibration, is done without the front aperture of the radiometer. The lamp is operated at the non-standard distance of 1.00 m to eliminate possible vignetting. The calibration is actually a validation in that the predicted theoretical TR calibration is compared to that based on the known source output. Preliminary results indicate that the calibration meets anticipated accuracy requirements.

The FEL lamp illuminating a diffuser panel provides a radiance calibration. The panel is illuminated at an angle of 45 degrees from a distance of 50 cm. This approach can be compared to the radiance-based calibrations using the RSG's SIS and one using a diffuser panel illuminated by the sun. Final results from the radiance-based methods are still under evaluation at the time of this report.

4.2. Multispectral to Hyperspectral Conversion

The ultimate goal of the TRs is to provide highly accurate measurements of source radiance at multispectral resolution. The multispectral results are converted to hyperspectral using various methods that were evaluated here. The results of this work showed that the maximum uncertainty expected from a 20-band TR in the VNIR results in uncertainties in the predicted output of a sphere source of less than 0.5% between 400 and 1000 nm (ignoring atmospheric absorption effects).

The performance of the VNIR TR was predicted for a typical sphere source using quartz halogen lamps. There are three main sources of error that were considered in this work; 1) Errors that are intrinsic to the curve fitting of the measured data, 2) errors that are due to the errors in the measured data (i.e., instrument characterization, filter ambiguities, noise, etc.), and 3) errors introduced solely from sampling issues (i.e., number of filters, band width of filters, band centers of the filters, etc.). The current work only includes evaluations of the wavelength region from ~350 nm to 1200 nm. Future work will include extending the models to include the SWIR region.

Source modeling estimates the hyperspectral output of three different sources as inputs; 1) A modeled SIS based on a blackbody radiator perturbed by the spectral reflectance of BASO4, 2) the RSG sphere as measured using a calibrated ASD spectrometer and smoothed, and 3) the Calibration curve from the sphere used at the Hanscom facility.

The instrument used in the modeling effort relied on the specifications of the VNIR TR's entrance aperture, detector size or second aperture area, the separation of the two apertures, the detector response for the trap detector, the filters spectral transmittances, and the center wavelength of each filter. The filter transmittance profile is modeled using combinations of Gaussian distributions and four basic profiles were included (Single Gaussian, Flat top, Asymmetric right, and Asymmetric left). The spectral response for a particular channel is determined by multiplying the throughput by the spectral detector response and the spectral filter transmission profile.

The band-averaged radiances are determined for each modeled filter of the VNIR radiometer and fitting is done based on an approach defined by NIST. The approach estimates the temperature via a Wien's law linearization and the estimated temperature determines the blackbody radiance based on Plank's law and the emissivity of unity. The radiometer "measurements" are compared to the blackbody values to determine a spectral emissivity which is fit spectrally using a polynomial or a cubic spline. Originally, it was suggested that a 5th order polynomial be used to fit the emissivity, but after several trial runs with the code, it was determined that a cubic spline produced a better estimate of the emissivity of the source.

Application of the approach provides a predicted hyperspectral source output for comparison to a known source. Results have been obtained for each of the three sources as well as for 10, 20 and 85 filters (each having a flat-top profile and a 10-nm bandpass FWHM), placed between 350 and 1200 nm. This effort is not meant to optimize the position of each filter but rather as a comparison of hyper-spectral measurement versus multispectral.

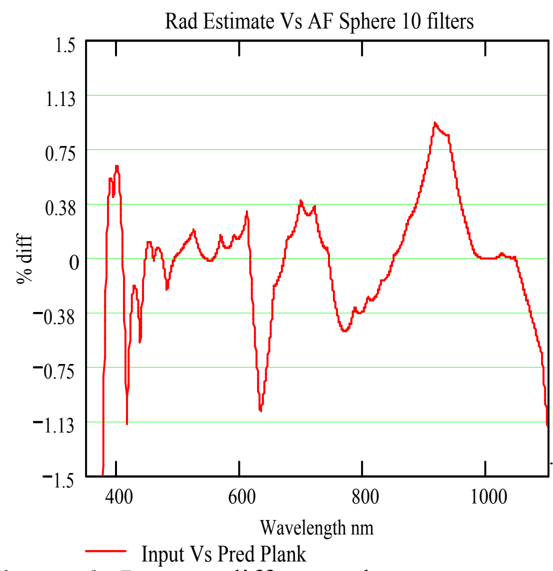

Figure 6. Percent difference between output of Hanscom SIS and that predicted from 10 bands.

Figures 6-8 show the results of the comparisons. The differences between the predicted and known source output are all less than 1.2% for bands between 370 and 1200 nm for all cases. The addition of 10 bands to give a total of 20 bands reduces the error to less than 0.8%. The best fit, as expected, is for the 85 spectral bands. The results for all cases is large for spectral bands less than 370 nm indicating that accuracy will be limited in these bands unless further information from another instrument such as a spectrometer can be used to refine the curve fit.

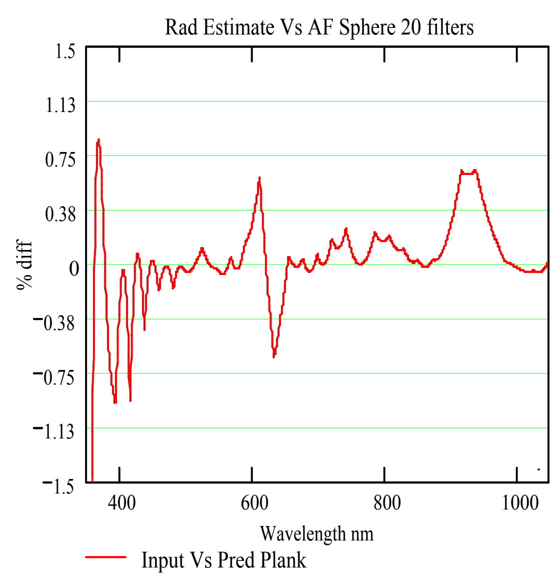

Figure 7. Percent difference between output of Hanscom SIS and that predicted from 20 bands.

Preliminary work has taken place evaluating the selection of a minimum number of multispectral radiometer measurements while giving an optimal approximation of the original hyperspectral measurements. The genetic algorithm (GA) is an optimization procedure that is widely used in minimization of multi-variable problems. GA is perfectly suited for the problem at hand: given a continuous curve reconstructed from an interpolated set of values (spectral measurements obtained from selected filter positions), an approximation curve results. The sum squared error between the original 'truth' curve and the interpolation is obtained. Filter placement is modified, a new interpolation computed, and a new root summed squared error is obtained. The GA manages these processes efficiently, keeping only those results which continuously improve the approximation. This approach is being used to develop the optimal selection of SWIR TR spectral bands.

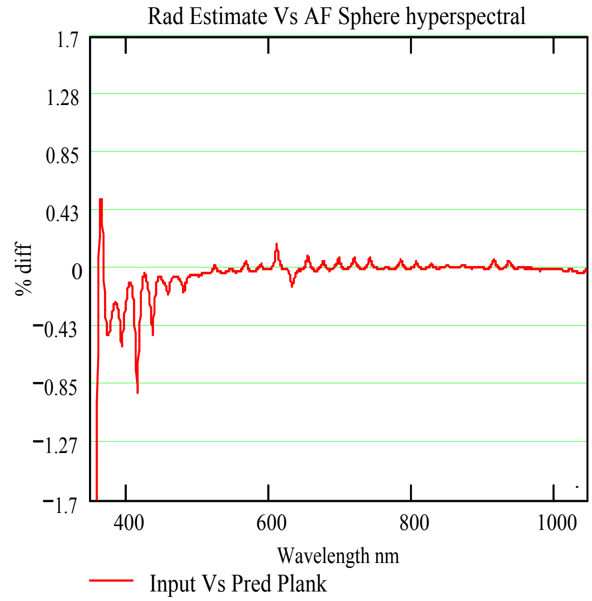

Figure 8. Percent difference between output of Hanscom SIS and prediction from 85

5. CONCLUSIONS

The work conducted during the first year of this project included the development and characterization of a highly accurate, ultrastable radiometer in the VNIR portion of the spectrum. The VNIR TR is the initial hardware developed as part of a facility for the characterization and calibration of hyperspectral imagers. Early evaluation of the radiometer shows that it is behaving at a level equal to, or better than, the original.

The VNIR TR becomes a key element in the prediction of source output at hyperspectral resolution. The work here has developed methods both to interpolate/extrapolate the multispectral TR measurements to hyperspectral resolution as well as methods to evaluate the accuracy of such approaches. These methods become integral to the development of a comprehensive calibration/validation plan which will be essential for the accurate characterization of hyperspectral imagers.

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List of Symbols, Abbreviations, and Acronyms

FOV	Field of View
FWHM	Full-width half maximum
GA	Genetic Algorithm
RSG	Remote Sensing Group
SRBC	Solar-radiation based calibration
SWIR	Shortwave infrared
TR	Transfer Radiometer
VNIR	Visible and near infrared